Long-term variations of the green corona (530.3 nm) irradiance

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Abstract. There is growing evidence that solar variability influences the heliosphere, biosphere and Earth's climate. The solar variability finds its representation via a large number of phenomena and structures observed in the solar atmosphere. Changes in the green corona irradiance over solar cycles are very pronounced and their long-term temporal behavior is in a good agreement with the corresponding variations of the solar magnetic flux, the latter being generally agreed to be the agent responsible for all aspects of solar activity. The green corona irradiance index exhibits a very good correlation not only with other solar indices, e.g., the 2800 MHz radio flux, the X-ray flux and the total solar magnetic flux, but also with cosmic ray flux (in the inversion course). Measurements of the total magnetic flux and some "space-borne" indices have been available since 1978, or around this period. On the other hand, the green corona index has already been available since 1939. In the present work, a long-term pattern of the green corona irradiance, as expressed in terms of the coronal index of solar activity (CI) and based on a homogeneous coronal data set, was compared with the corresponding behaviour of the number of sunspots, the 2800 MHz radio flux, the total magnetic flux and cosmic rays, and this comparison yielded a remarkable good correlation between these indices in the period of 1947–2004. So, employing the correlation between the CI and sunspot numbers provides us with a unique tool to extrapolate the CI back to 1848, or even to the earlier years. The extended CI thus obtained is then compared with other similarly reconstructed solar indices. Cycle-to-cycle variations (17–23 cycles) of the CI are also discussed.

Index Terms. 530.3 nm corona, irradiance, long-term variations.

1. Introduction

There are several emission lines observed in the solar corona, e.g., the 530.3 nm (the green line, Fe XIV), the 637.4 nm (the red corona, Fe X), and the 569.4 and 544.5 nm (the yellow lines, Ca XV). Each of them varies in its intensity over a solar cycle, reflecting the physical conditions across the corona in dependence on the local magnetic field configurations in the photosphere. The best indicator of the solar variability in the emission corona is the green line intensity, e.g. (Waldmeier, 1957; Leroy and Trellis, 1974; Altrock, 1988; Makarov, Tlatov and Callebaut, 2003; Ru_in et al., 2004).

The solar corona is the outermost – very hot and diluted – layer of the solar atmosphere; its temperature is of about 2 million degrees and electron density of 10^8 cm $^{-3}$. The green line intensity is visible during a complete 11-year solar cycle activity and around the entire solar limb. Measurements of the green coronal intensity represent one of the longest-running direct indices of solar activity, being surpassed only by the sunspot number (available since 1610), sunspot area (since 1874) and calcium plage index (since 1905; Lean, 2000, and references therein). Therefore, the green corona intensity can easily be compared with similar solar indices inferred from both ground-based and space-borne experiments within the past few decades. Hence, employing a well-pronounced correlation between the CI and the 2800 MHz radio flux one could extend several indices back to 1939, while using the relation between the sunspot number and the CI a similar extension of the CI (for the Sun as a star) can go as far as to 1848, or even earlier.

2. Coronal index of solar activity

Although first studies of the emission spectral line of the 530.3nm (see Fig. 1) can be dated back to 1939, its first systematic observations and analyses began only after the World War II.

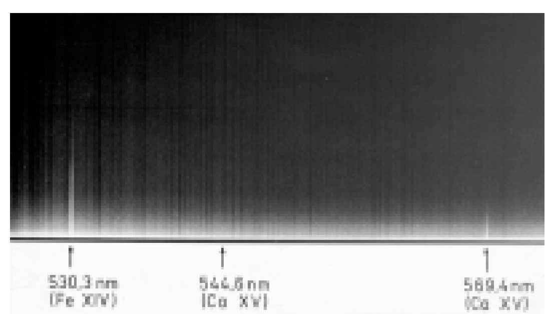

Fig. 1. A typical pattern of coronal emission spectral lines, together with "parent" ions indicated below.

It was soon realized, however, that the observed intensities of the green corona were different from different coronal stations (Rybansk_ et al., 2005). The main reasons for such discrepancies were different strategies/methodologies of acquiring the data, the height of observing above the solar limb, etc. There were a number of attempts to unify this kind of observations, yet up to date all these attempts have been unsuccessful. In this paper, we shall employ the data transformed to the Lomnick_ _tít photometric scale.

To facilitate comparisons of ground-based green line measurements with observations in extreme ultra-violet and soft X-ray wavelengths made from space, (Rybansk_, 1975) proposed a new index of solar activity based on Lomnick_ _tít 530.3 nm measurements that he called the "coronal index of solar activity" (CI). The CI expresses the irradiance of the green corona for the Sun as a star and can easily be compared with similar full-disk solar indices. CI values are expressed in power units [W sr^{-1}] and can straightforwardly be transferred to similar units obtained from space-borne measurements as shown below:

10^{16} W sr^{-1} _ 4.5 x 10^{-7} W m^{-2} (at 1 AU)

_ 1.2 x 10^{8} photons cm^{-2} s^{-1}. (1)

Monthly averages of the CI for the period from 1939 to 2004 vary from 2 x 10^{16} W sr^{-1} (around cycle minima) to 20 x 10^{16} W sr^{-1} (around cycle maxima). Daily CI maximum values have never exceeded 30 x 10^{16} W sr^{-1}. The green line intensity in calibrated observations is expressed in absolute coronal units (ACU). One ACU represents the intensity of the continuous spectrum of the center of the solar disk in the width of 1 Å, at the same wavelength as the observed coronal spectral line (1 ACU = 3.89 W m^{-2} sr^{-1} at 530.3 nm).

Based on the "consensus", in 1947, between several observers of the corona, coronal intensities are derived at least once a day at heights of 40 – 60 arcsec above the solar surface with a lag of 5 degrees in the positional angle. An example of such an observation is shown in Figure 2.

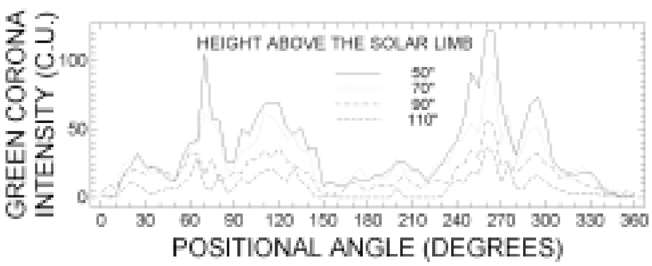

Fig. 2. Plots of the green line intensities, expressed in absolute coronal units, as measured at different heights above the solar disk at the Lomnick_ _tít coronal station on June 5, 2002.

The initial observation is made above the solar north pole, and 71 subsequent data points are made at the same height proceeding in the counterclockwise direction (north, east, south, west) (d'Azambuja, 1947). The CI for a given day is based on limb observations of the green line for that day and intervals of six days on either side of that day. The distribution of the intensity above the solar surface is obtained by using the observations at the E-limb (W-limb) from the six days preceding (following) the given day to specify the coronal intensities above the eastern (western) half of the disk. By integrating over the solar disk, we obtain the irradiance in front of the visible part of the Sun (E_H) to which we add the irradiance above the solar limb (0.5 E_L) (see Figure 2 in Rybansk_, 1975) to obtain the coronal index

$$CI = E_H + 0.5 E_L, \quad (2)$$

which is the total irradiance of the green corona into one sterradian (sr) towards the Earth (see Rybansk_, 1975, for more details).

Today, the CI is widely used for a study of solar variability. A comparison of the CI prior to the (Rybansk_ et al., 2005) analysis, as illustrated by Fig. 3, indicated that the homogeneous coronal data set from which the CI is computed needs to be reexamined and modified for years before 1966, as well as for several short periods in 1966 – 2002. Both the revised and old CI's are depicted in Figure 4, together with their differences.

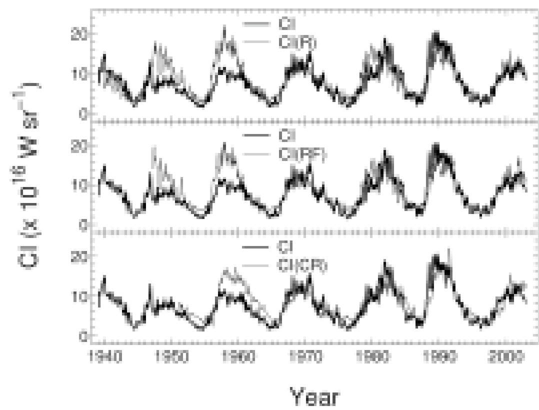

Fig. 3. Monthly averages of the CI from 1939 to 2002 (heavy lines) compared with the proxy CI indices (thin lines), taken from (Rybansk_ et al. 2005).

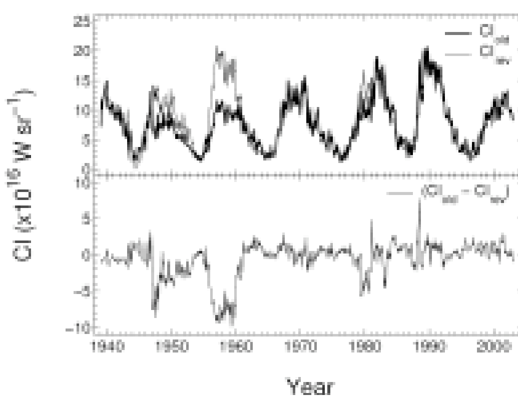

Fig. 4. A plot, for 1939–2002, of the old and revised CI monthly means (top) and their difference (bottom).

3. The green corona and similar solar indices

It is a firmly established fact that the intensity of the green corona is, in general, well correlated with the distribution of local solar surface magnetic flux (Wang et al, 1997; Zhang et al. 1999; Ru_in and Rybansk_, 2002). It is also a well-known fact that local magnetic fields are responsible for all the major manifestations of solar activity. This implies that there must be a high correlation between the behavior of the CI and other full disk solar variability indices such as the 2800 MHz radio flux (Fig. 5), sunspot number (Fig. 6) and cosmic rays (Fig. 7), as it is indeed the case.

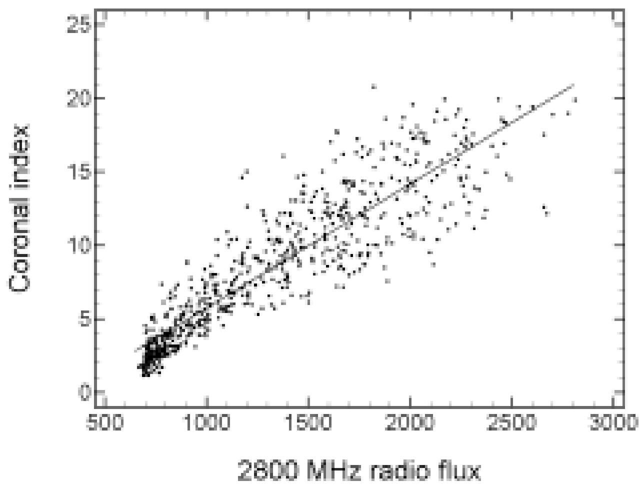

Fig. 5. Correlation between the CI and 2800 MHz radio flux (monthly averages). The correlation coefficient is 0.900.

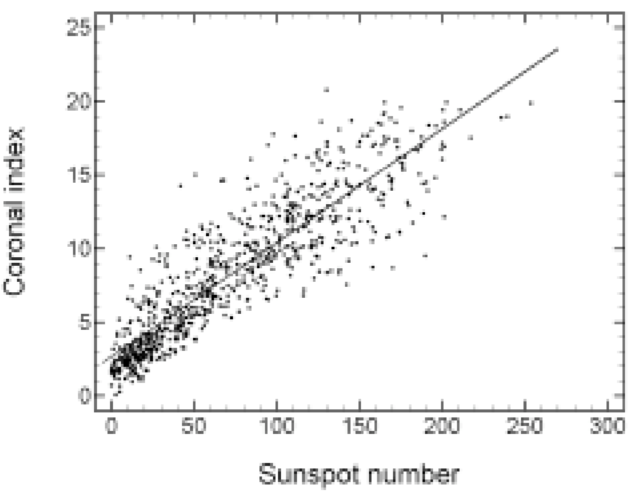

Fig. 6. Correlation between the CI and sunspot number (monthly averages). The correlation coefficient is 0.883.

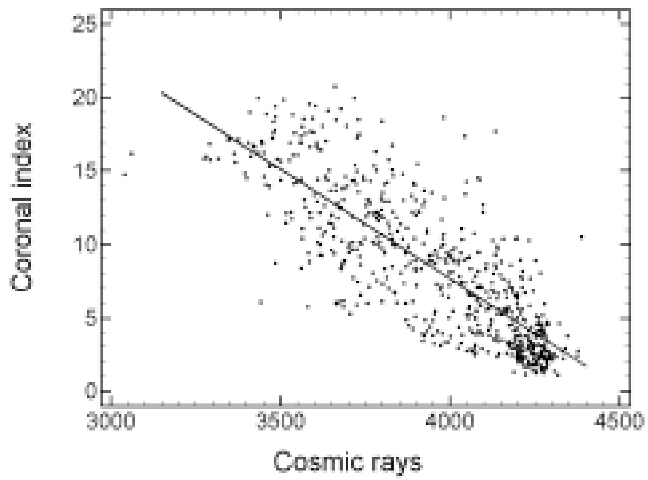

Fig. 7. Correlation between the CI and cosmic rays (monthly averages). The correlation coefficient equals 0.812.

A similarly high coefficient of correlation was, in 1976–2002, found between the green line intensities and magnetic flux (cc=0.869, Ru_in and Rybansk_, 2002) as well as between the CI and the X-ray flux (cc=0.864) as obtained from space-borne equipments (Rybansk_, Minarovjech and Ru_in, 2003). To check an intricate relation between the CI and solar total magnetic fields we have compared the CI with the absolute magnetic flux (expressed in Gauss) as obtained at the Kitt Peak solar observatory in 1997–2004; this comparison is shown in Figure 8.

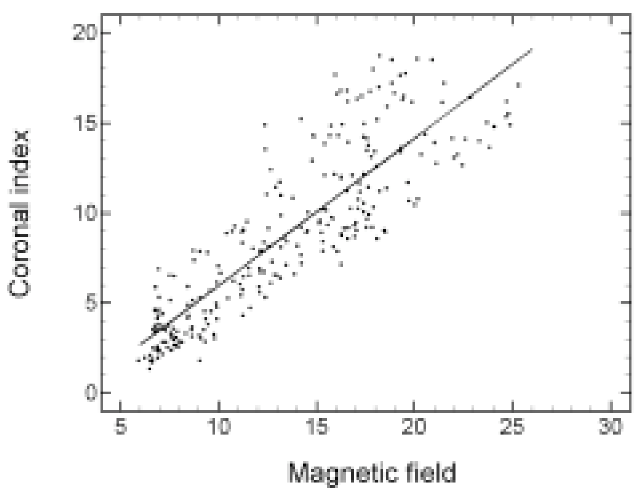

Fig. 8. Correlation between the CI and the Kitt Peak magnetic flux data (27-day averages). The correlation coefficient equals 0.864.

All in all, the CI, which ranks amongst the oldest "energetical" indices, can well be used for studies of solar activity from as early as 1939. In addition, with its help we can extrapolate all "modern" indices (Total Solar Irradiance, Magnetic Flux, etc.) back to 1939. On the other hand, a well-established correlation between the CI and sunspot number can be used to extrapolate the former back to 1848 (see Fig. 9).

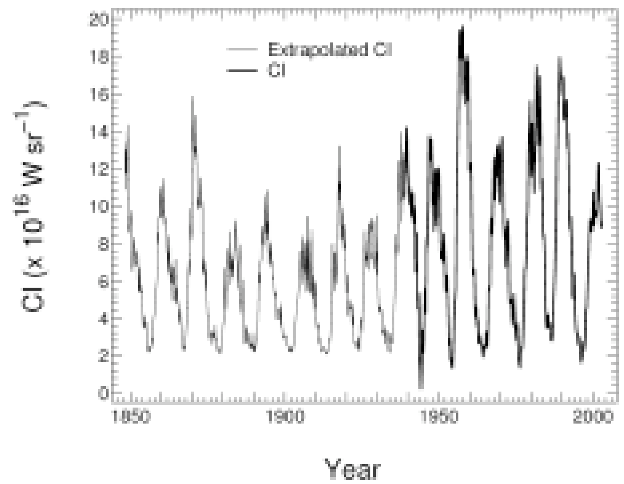

Fig. 9. Monthly averages of the CI (1848–2002). Heavy line – CI_{rev} (1939–2002), thin line – the CI extrapolated from the sunspot number (1848–1938).

The CI obtained this way can be compared with a reconstructed magnetic flux and/or the total flux discussed by (Krivova and Solanki, 2003 and references therein), with the empirical reconstruction of magnetic flux by (Loockwood et al., 1999) and the concentration of the ^{10}Be isotope in ice cores by (Beer et al., 1990). From the above-described statistical analyses we have arrived at the following relations, valid on a statistical (i.e. average) basis, between the CI and 2800 MHz radio flux (RF), cosmic rays (CR), sunspot number (SN) and magnetic flux (MF), respectively:

CI = 0.00841 RF – 2.655,

CI = – 0.149 CR + 67.3,

CI = 0.0755 SN + 2.638,

and

CI = 8.81 MF – 2.229.

4. Cycle to cycle variability of the CI

The intensity of the green corona has been measured since 1939, which is a sufficiently long period to find out its changes not only within a solar cycle, but also between individual cycles, as depicted in Fig. 10.

Daily measurements clearly demonstrate that the intensity of the green corona is always enhanced above active regions in the photosphere, which move from middle heliographic latitudes at the beginning of a cycle towards the equator. An illustrative example of a time-latitude distribution of the local maxima of the intensities of the green corona is shown in Fig. 11 (see Minarovjech et al., 1998 and Ru_in et al., 2000).

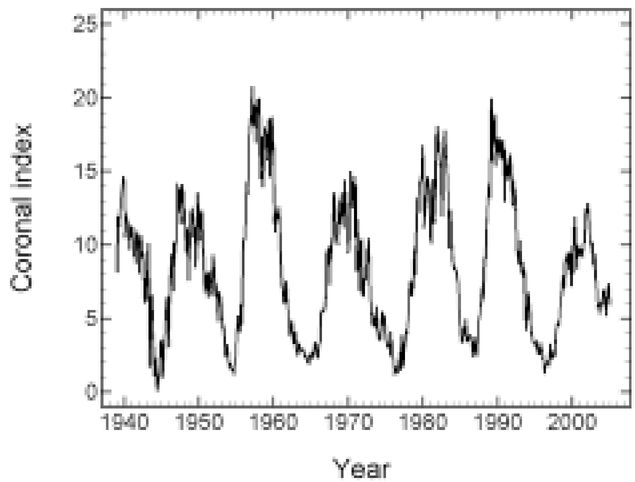

Fig. 10. Monthly averages for the CI in the period 1939–2004.

The ratio between the intensity of the green corona above the polar regions and that measured above active regions varies within a cycle from the value of about 1:4 around minima to 1:20 around maxima. If we look at Fig. 10, we see that this variation is fairly good mimicked by the behaviour of the CI, which yields the ratio 1:5–9. It is worth mentioning that these variations are not induced by the changing average temperature of the corona, but stem from the variations of the electron density and the number of associated active regions.

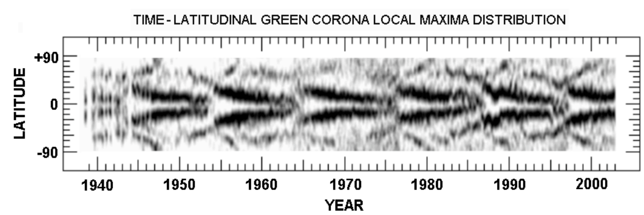

Fig. 11. Time-latitudinal distribution of the local maxima intensities of the green corona as derived from the homogeneous coronal data set.

A similar comparison between individual cycles also yields variability, although much less pronounced – 1:1.5. If in our earlier work (Ru_in et al., 2004 and references therein) we found out that the maxima of the last five cycles are characterized by a gradual increase of the CI, our latest analysis with the revised data did not confirm this trend; this feature persists only for the cycles 21 to 22 and 17 to 19, although in the latter case one has to be a bit cautious due to a large number of extrapolated data in cycle 17 due to sparse observations. It is also interesting to note that the values of the CI in cycle 23 are the lowest ones for the whole period under study.

A frequently discussed phenomenon is the so-called “double-maxima” phenomenon (also known as the “Gnevyshev gap”), discovered in 1963 by (Gnevyshev, 1963). This phenomenon also finds its reflection in other manifestations of solar activity and cosmic rays as well (Storini et al., 2003) and we have discussed it in detail in (Rybansk_, Minarovjech and Ru_in, 2003). We suggested that the distribution of the maxima of the intensities of the green corona is more or less of random nature, and different for the northern and southern hemispheres. From Fig. 10 we cannot say with certainty when the maxima of the green corona's intensities are correlated with (i.e., occur approximately 1.5 to 2 years later than) the maxima of sunspot number. The most remarkable in this respect was cycle 21, when the CI maxima were observed in 1982, while those of sunspot number in 1979; in this particular cycle the maxima of the CI also coincided with those of cosmic ray, soft X-ray flux (Veroning et al., 2004), and of the Ca II K 1.0 A intensities (Lean, 1987). Something similar has been observed in the last 23 cycle. There are several scenarios of how to explain this behaviour, e.g., dynamic energy balance in the corona (Wheatland and Litvinenko, 2001) and/or connection with a magnetic field reversal in odd- and even-numbered cycles. Mavromichalaki et al. (2002) came to the conclusion that the occurrence of maximum green coronal line intensities is connected with the distribution of photospheric magnetic fields.

5. Summary

The work focused on the behavior of the CI in the period from 1939 to 2004 and its comparison with distributions of other long-term indicators of solar activity such as the 2800 MHz radio flux, sunspot number, cosmic rays and total magnetic flux. We have found a good correlation between these indices. This enabled us to extrapolate all the modern indices up to the beginning of the corona's observations, and the CI up to the beginning of sunspots' observations. We have also found that the maxima of the CI differ from cycle to cycle, with no clear-cut pattern behind. It is, however, obvious that the CI is not only a good quantitative indicator of solar activity in the corona, but also a reliable "energetical" index which serves as a substitute and background for many indices based on space-borne observations. It is also an index which has much to stay to solving the problems connected with influence of the heliosphere on the (climate of the) Earth — the problems which are of crucial importance in programmes like 'Living with a Star' and 'Space Weather'. After all, solar activity has impact on numerous scientific and practical areas, e.g., space operations, electric power transmissions, cosmic ray flux, climate impact, etc. So, the study of the solar irradiance in many long-term indices is very important. Finally, we mention that the revised values of the homogeneous set of data of the intensities of the green corona and those of the CI itself are available for free on http://www.ta3.sk/corona.

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